Experimental Searches for Neutron Antineutron Oscillations

Leah Broussard
Oak Ridge National Laboratory

BLV circa 2020 workshop
July 6-8, 2020

Violation of Baryon Number B

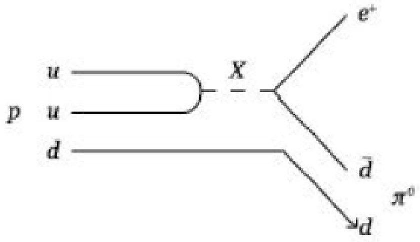
- B, L are accidental symmetries
  - Violated at non-perturbative level; $B - L$ conserved in the SM
- BNV could explain BAU
- Target $\Delta B \neq 0$ & $\Delta[B - L] \neq 0$
  - $n \to \bar{n}$, dinucleon decays sensitive to BNV-only; $n \to \bar{n}$ offers cleanest approach
  - BSM models that predict BNV predict $n \to \bar{n}$
- x1000 improvement in $n \to \bar{n}$ sensitivity on horizon!

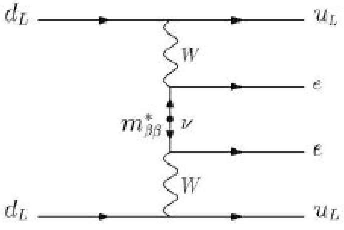
$$\boxed{\Delta B \neq 0\ ,\ \Delta L = 0,\ \Delta[B - L] \neq 0}$$

$$\Delta B = 0\ ,\ \Delta L \neq 0,\ \Delta[B - L] \neq 0$$

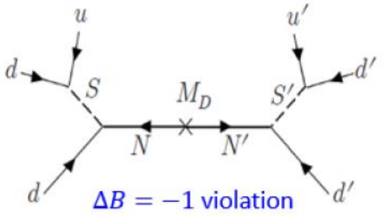
$$\Delta L \neq 0\ ,\ \Delta B \neq 0,\ \Delta[B - L] = 0$$

Complementary Approaches

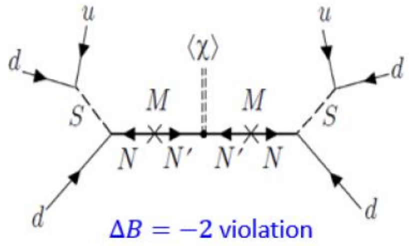




Z. Berezhiani > 2006



$\overline{B} = B + B'$ conserved !



$$p \to e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$

$$0\nu 2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$

Symbiosis

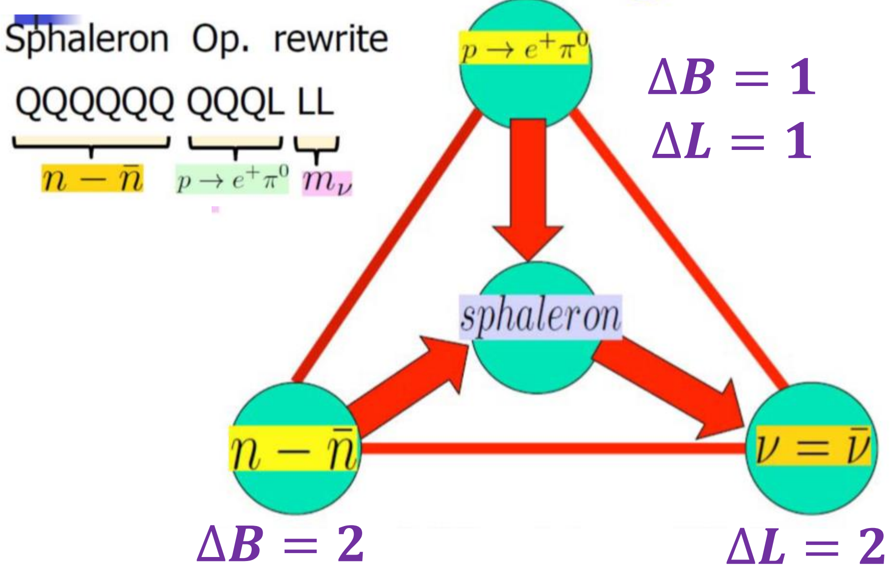
$$n \to \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$

$$n \to n' \text{ (mirror)}$$
$$\Delta B = 1, \Delta L = 0$$

Connection to dark sector, neutron lifetime anomaly

- Neutron oscillations under-explored!
- Symbiosis with 0νββ: L-R unification theories predict both.

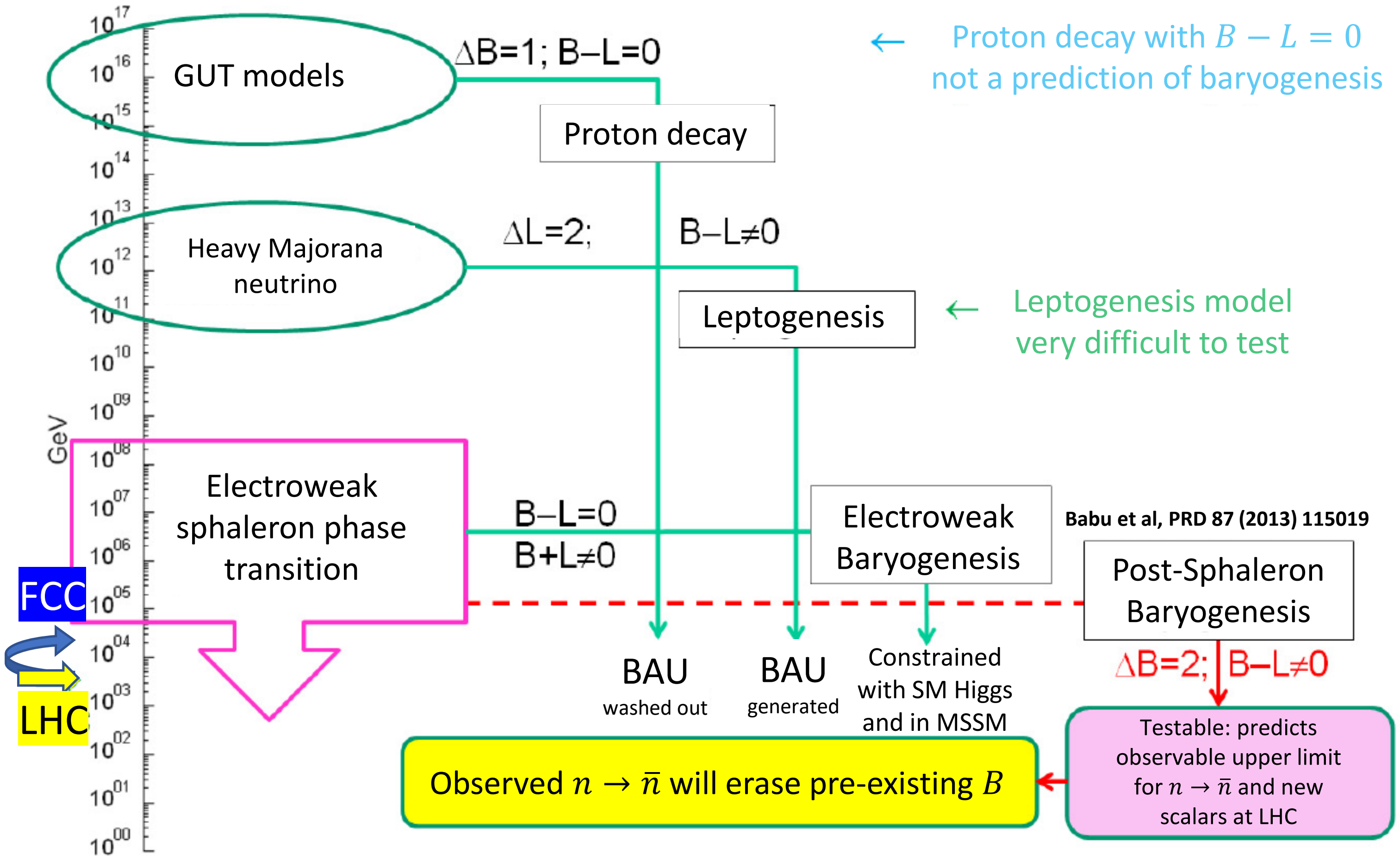
B-L Triangle:



from R. Mohapatra

Baryogenesis Models

- Regimes for baryogenesis
  - Leptogenesis: Sphalerons convert L into B
  - Electroweak baryogenesis: T violation near EW scale creates B without L
  - Post-sphaleron baryogenesis: New BNV process below EW phase transition
- $n \to \bar{n}$ targets accessible energy scales
  - null result can rule out e.g. PSB



$n \to \bar{n}$: Timely Opportunities

- Previous Snowmass: BNV mentioned but no priority recommendations to address
- $n \to \bar{n}$ impacts BAU without need for additional interpretation
- Strong worldwide community support for $n \to \bar{n}$ program
- Opportunities in DUNE and ESS: requires action
  - Possibility to improve free search sensitivity by x1000
  - Complementarity: various models predict different relative strengths for bound vs free $n \to \bar{n}$
- Program of development in last decade and next
  - Bound neutrons: improving analysis and understanding uncertainties in a DUNE search
  - ORNL program—near term activities for $n \to \bar{n}$ R&D with complementary science goals
  - $3M Horizon 2020 EU project for a design study for $n \to \bar{n}$ activities at ESS

Neutron Oscillations

- Mixing of 2 state system with potential difference V for neutron vs antineutron
  - Nuclear potential (100 MeV)
  - Earth magnetic potential $\mu \cdot B$ (10^{-18} MeV)
  - Strong limits on $\tau_{n\to\bar{n}}$: Mass splitting from any nonzero V >> off-diagonal term $\varepsilon < 10^{-29}$ MeV

$$\hat{H} = \begin{pmatrix} E+V & \varepsilon \\ \varepsilon & E-V \end{pmatrix}$$

$$\varepsilon = 1/\tau_{n\to\bar{n}}$$

- Free neutrons require strong cancellation of magnetic fields ("Quasi-free limit" estimate from uncertainty principle) < 10 nT
  - $P_{n\to\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\to\bar{n}}}\right)^2$
- Bound neutrons "free" inside nucleons for $\Delta t \approx \hbar/E_{binding} \sim 5 \times 10^{-22}$ s
  - Nuclear suppression factor
- Figure of merit (background-free): Nt^2

Neutron Oscillations

- Straightforward extension of formalism to consider $n \rightarrow \bar{n}, n', \bar{n}'$
- General mixing of neutrons with or without dark sector
- Focus in this topic on $n \rightarrow \bar{n}$
    - Classic signature: single mixing term $\varepsilon_{n\bar{n}}$ independent of dark sector
    - Possible pathway via sterile neutron state $n \rightarrow (n', \bar{n}') \rightarrow \bar{n}$ [1]

$$\hat{\mathscr{H}} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$

- For general searches to probe mixing with dark sector, primarily focus on RF6: Dark Sector Studies at High Intensities
    - https://snowmass21.org/rare/dark

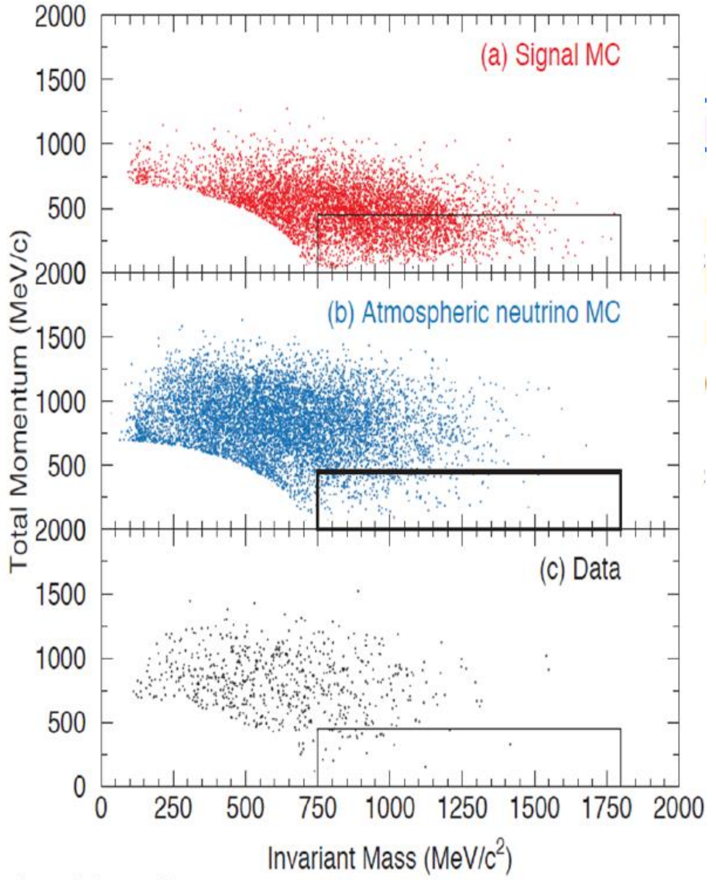
[1]Z. Berezhiani, arXiv:2002.05609 (2020)

Prior $n \to \bar{n}$ Searches

Nucleus	Experiment	n · year (10^{32})	$\tau_{n\to\bar{n}}$ (10^8 s)
16O	SK-I (2015)	1.9	2.7
16O	Kamikande (1986)	0.4	1.6
2H	SNO (2017)	0.1	1.4
56Fe	Soudan II (2002)	0.7	1.3
56Fe	Frejus (1990)	0.7	1.2
16O	IMB (1984)	0.2	1.2
free n	ILL (1994)	—	0.9

Best published limits from SuperKamiokande [1]

- 24 candidate events and 24.1 expected background events
- T>1.9 x 10^{32} years;
  τ > 2.7 x 10^8 s; R= 0.517×10^{23}/ s



Adapted from Ed Kearns

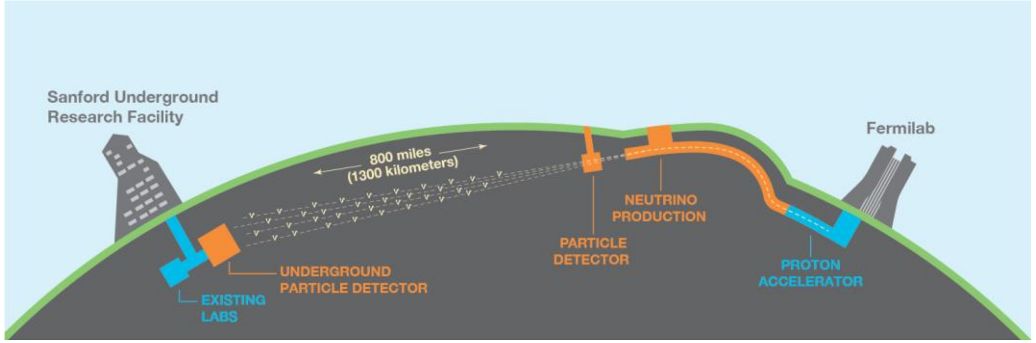
- **Activity ongoing**—preliminary SK-I/II/III/IV result [2]: 3.6x10^{32} years at 90% C.L, τ > 4.7 x 10^8 s (Join the August BNV=2 Workshop for more info!)
- DUNE and Hyper-K future opportunities to expand sensitivity further

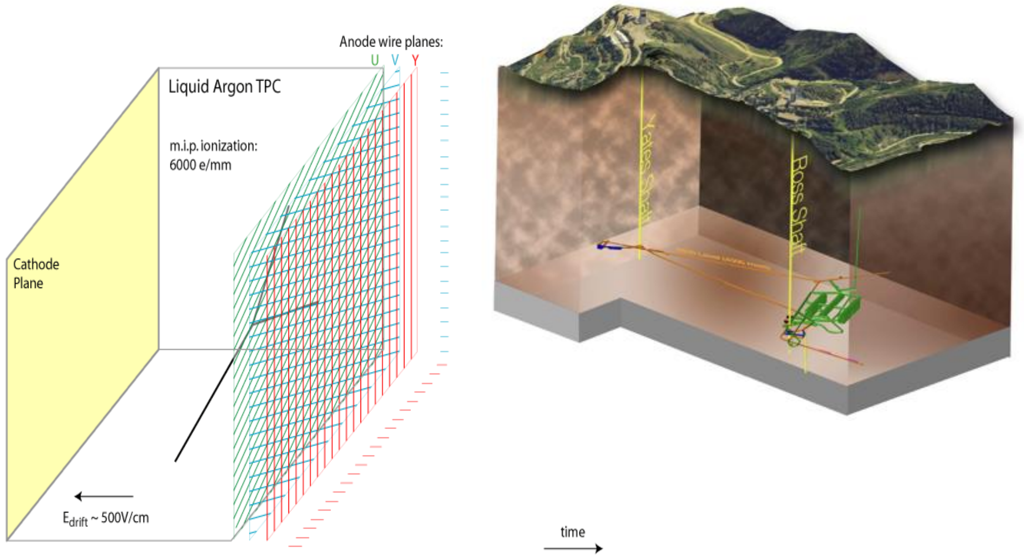
- Last free neutron search in 1994 [3]
  - HIBEAM program can achieve similar sensitivity
  - NNBar at ESS could be definitive experiment with x1000 improvement in sensitivity

[1] Abe et al, PRD 91 072006 (2015)
[2] L. Wan, Neutrino 2020
[3] Baldo-Ceolin et al, ZPC 63 409-416 (1994)

Deep Underground Neutrino Experiment and Intranuclear $n \rightarrow \bar{n}$ Searches

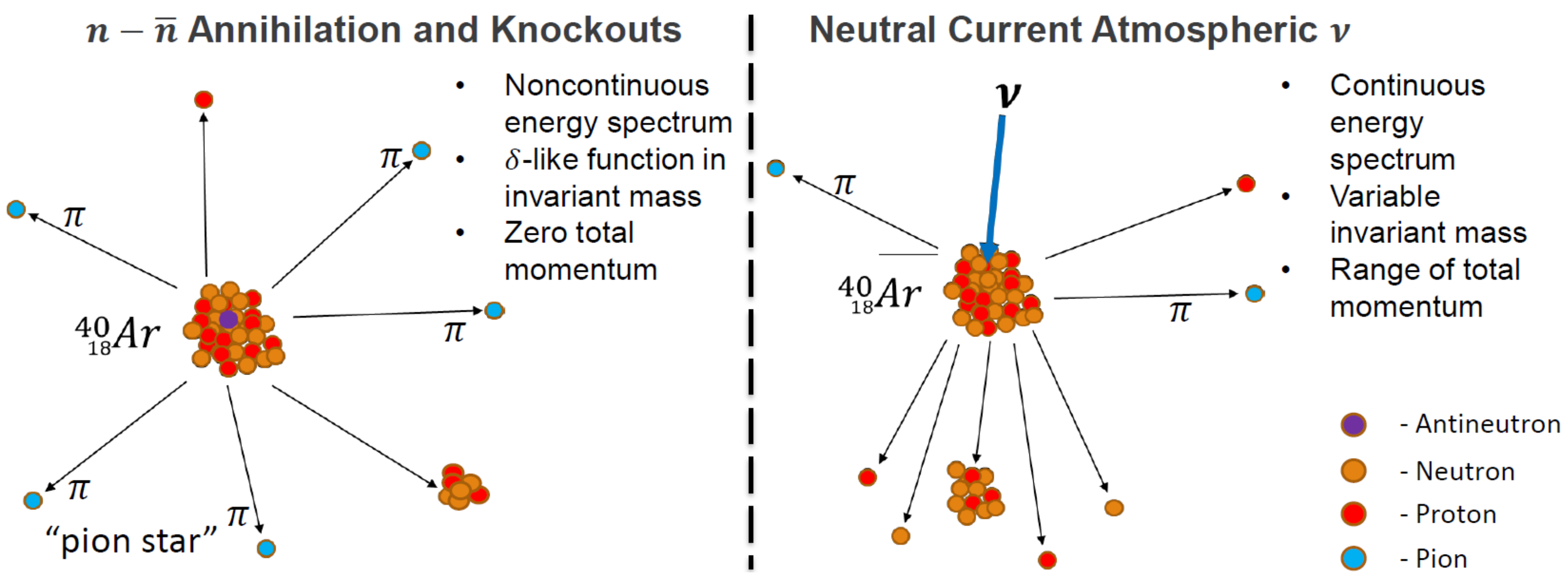
- DUNE Far Detector: large mass LArTPC
  - 1.5 km underground, 4 10kton LAr modules
  - Offer low KE threshold (e.g. protons), higher resolution, bubble chamber-like images, PID & dE/dx capabilities
  - Significant reduction in background rejection rate possible over Super K
- BNV in large ν detectors—featured topic in Neutrino Frontier, NF03: BSM
  - https://snowmass21.org/neutrino/bsm/





Slide content from Yeon-jae Jwa, Workshop on Particle Physics with Neutrons at the ESS, (2018)

Signature of $n \to \bar{n}$ in Nuclei



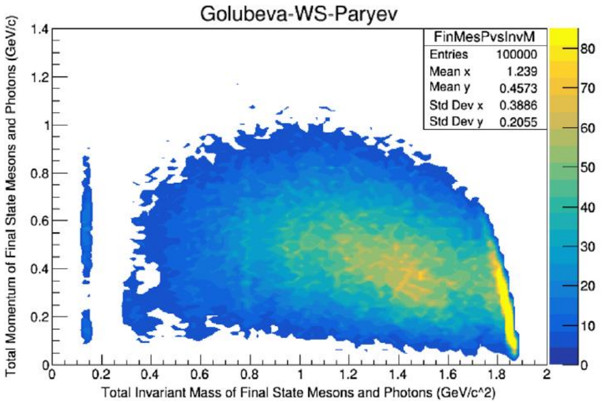
Approximations for most frequent modes (updated in PRD **99**, 035002 (2019))

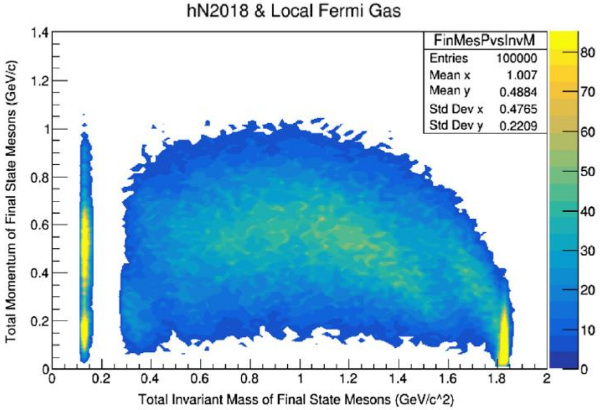
$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1.2%	$\pi^+\pi^-$	2.0%
$\pi^+2\pi^0$	9.5%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	11.9%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	26.2%	$\pi^+\pi^-2\pi^0$	11.0%
$2\pi^+\pi^-2\pi^0$	42.8%	$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+\pi^-2\omega$	0.003%	$2\pi^+2\pi^-$	7.1%
$3\pi^+2\pi^-\pi^0$	8.4%	$2\pi^+2\pi^-\pi^0$	24.0%
		$\pi^+\pi^-\omega$	10.0%
		$2\pi^+2\pi^-2\pi^0$	10.0%

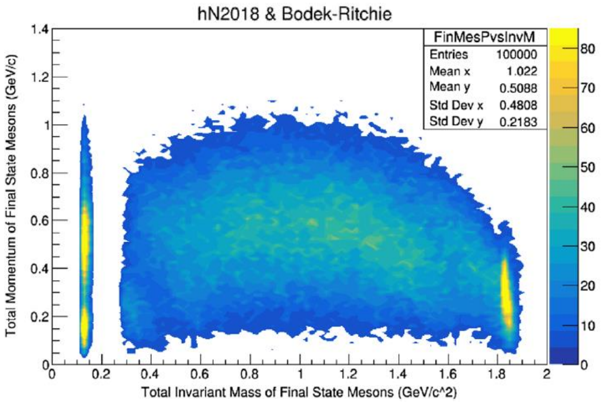
- Task: distinguish characteristic $\bar{n}$ signature ("pion star") from backgrounds such as ν_{atm} background (NC dominant), CC-produced τ decays
- Constraints: topology, 1.88 GeV, total momentum 0, average 5 pions

Event Generation for $n \to \bar{n}$

- Oscillated ν_{atm} background generation complete [1], LArSoft detector reconstruction chain implemented
- Expanding default model of $n \to \bar{n}$ signal to study impact of nuclear/intranuclear models on event generator to [2-3] (J. Barrow)
    - Make the models more realistic--local Fermi momentum model, different FSI assumptions, improved BR...
    - Includes re-estimate of $R_{Ar} \sim 5.6 \times 10^{22}$ s^{-1} → 12% lower sensitivity in T
    - 6 independent model configurations using GENIEv3.0.6; truth level complete, importing into LArSoft reconstruction chain
- Goal--investigate S:B stability with model choice, impact on T lower limit
    - Model-dependent inconsistencies could be a challenge, regardless of accuracy of background modeling







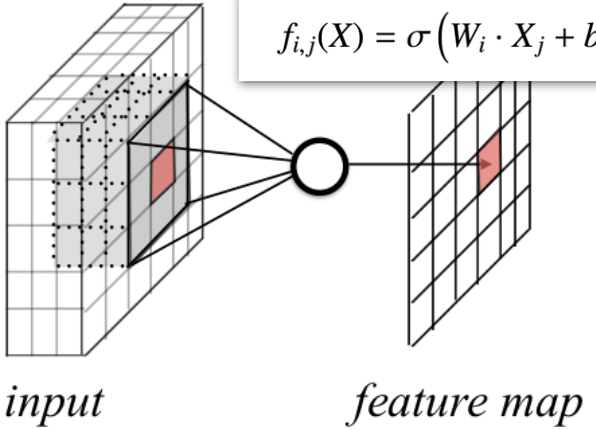
[1] PRL **123**, 081801 (2019)
[2] PRD **99**, 035002 (2019)
[3] PRD **101**, 036008 (2020)

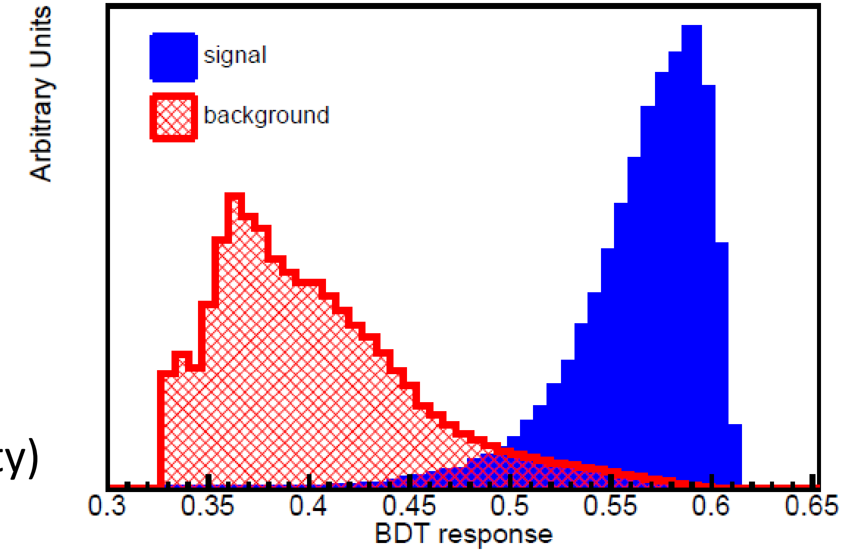
Analysis chain

- Event Generation
  - Default model (GENIE v2.12.10) used in DUNE analysis to date (TDR)
  - Geant4 tracking → detector sim → wire reconstruction → find ROI
- Distinguish S:B events using unique topological features → ideal for application of CNN (Y.-J. Jwa)
- Apply CNN signal score input into BDT classifier for event selection
- Best limit: T>6.45 x 10^{32} years; **τ > 5.53 x 10^8 s**;
  - R= 0. 666×10^{23}/ s (est. with ^{56}Fe)
  - signal efficiency 8.0%, background rejection 99.98%
- Study using new event generators in progress!
  - CNN PID studies for BDT input possible in coming months (C. Sarasty)

convolutional neural network

$$f_{i,j}(X) = \sigma\left(W_i \cdot X_j + b_i\right),$$

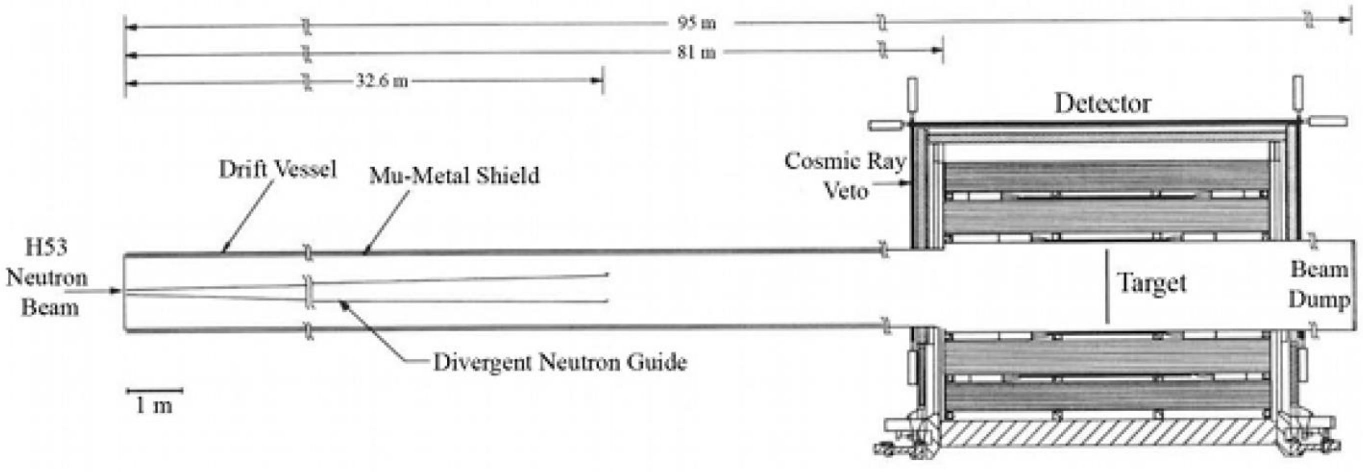


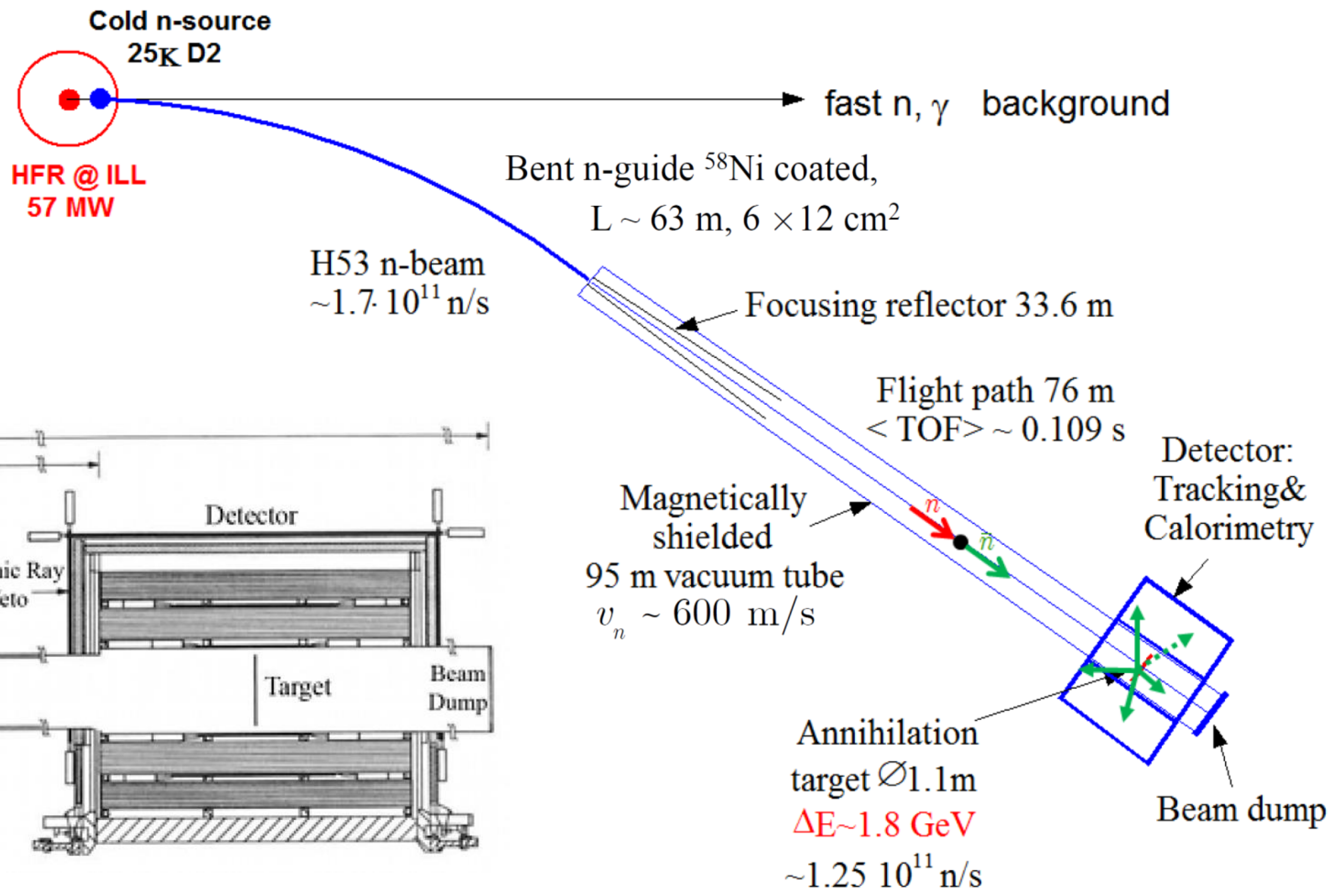


DUNE Far Detector Technical Design Report Volume II: DUNE Physics, arXiv:2020.03005
Slide content from Yeon-jae Jwa, Workshop on Particle Physics with Neutrons at the ESS, (2018)
Join the [August BNV=2 Workshop] for more details

Free $n \to \bar{n}$ Search at ILL

- Zero candidate events
- Zero backgrounds
- $\tau_{n\to\bar{n}} > 0.86 \times 10^8$s





- Major advances in neutronics and detector technology since

Baldo-Ceolin et al, ZPC 63 409-416 (1994)

NNBar Experiment at the ESS

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P. Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[be], G. Ichikawa[bf], T. M. Ito[ab], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[s], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[l], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,bn], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,av], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[a]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA, USA*
[b]*INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy*
[c]*Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA*
[d]*Department of Physics, Indiana University, 727 E. Third St., Bloomington, IN, USA, 47405*
[e]*Indiana University Center for Exploration of Energy & Matter, Bloomington, IN 47408, USA*
[f]*Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA*
[g]*Department of Physics, Boston University, Boston, MA 02215, USA*
[h]*Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China*

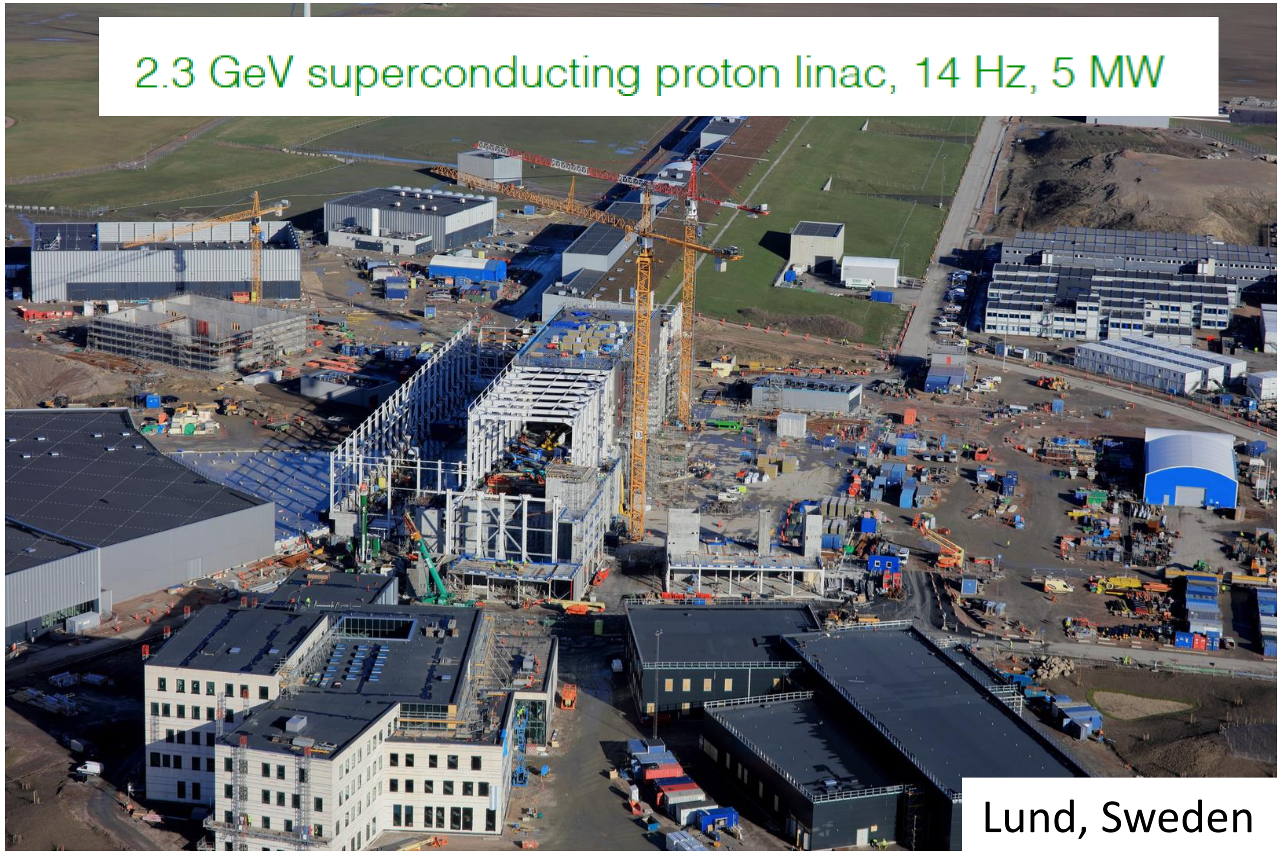
*Corresponding author: david.milstead@fysik.su.se

Preprint submitted to Elsevier *June 11, 2020*

University of Massachusetts, Laboratori Nazionali del Gran Sasso, Fermi National Accelerator Laboratory, Indiana University, Boston University, Boston, Sichuan University, University of Chicago, University of Maryland, University of South Carolina, Università di L'Aquila, National Institute of Standards and Technology, Petersburg Nuclear Physics Institute, Technical University Munich, Institut Laue-Langevin, University of Helsinki, Chalmers Tekniska Högskola, University of Houston, Houston, East Tennessee State University, Kennesaw State University, Indian Institute of Technology, The University of Tennessee, Knoxville, The Henryk Niewodnicza´nski Institute of Nuclear Physics, Polish Academy of Sciences, The University of Kentucky, Lexington, The University of Liverpool, Los Alamos National Laboratory, European Spallation Source, Lunds universitet, Technical University of Denmark, Johannes-Gutenberg-Universität, University of Minnesota, Russian Academy of Sciences, Lebedev Physical Institute, Moscow Institute of Physics and Technology, Institute for Theoretical and Experimental Physics, Moscow, Joint Institute for Nuclear Research, Dubna, Columbia University, Novosibirsk State University, Nagoya University, Oak Ridge National Laboratory, Oak Ridge, California Institute of Technology, North Carolina State University, INFN sezione Roma Tor Vergata, RIKEN iTHEMS Program, University of California Santa Barbara, Shanghai Key Laboratory for Particle Physics and Cosmology, Tong University, University of Sheffield, Washington University, Oklahoma State University, Stockholm University, Stockholm, Stony Brook University, International Centre for Theoretical Physics, Trieste, High Energy Accelerator Organization (KEK), University of Uppsala, Brookhaven National Laboratory, Universidad Técnica Federico Santa María, Université de Lyon, RIKEN, The University of Sydney, MAX IV Laboratory, Ludwig-Maximilians-Universität

European Spallation Source

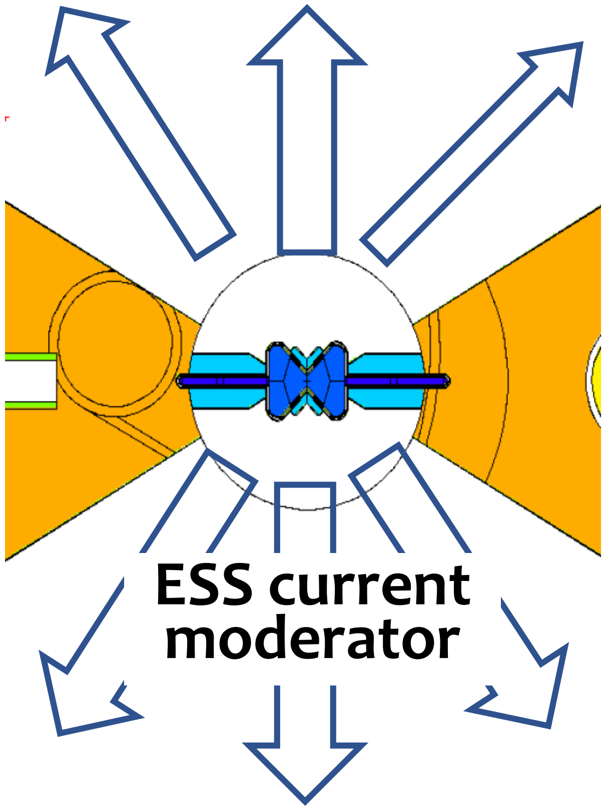
- ESS intended for n scatterers, but significant component to be fundamental physics research, including $\boldsymbol{n \rightarrow \bar{n}}$ **search**
- NNbar Collaboration: pursuing O($100M) search for nnbar
  - "Large Beam Port" constructed by ESS
  - LD2 cold moderator studies underway ("HighNESS - $3M Horizon 2020 EU project")
- Beamline earliest available ≥ 2030
- HIBEAM: smaller program of complementary experiments $\gtrsim$ 2023
- Collaborating with ORNL program (now underway)

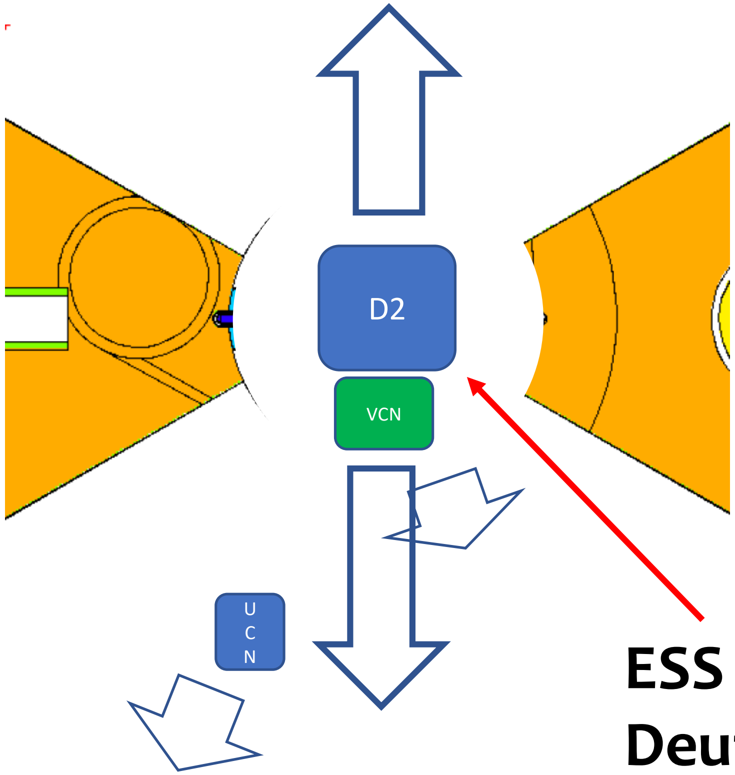


ESS Status: Construction 70% Completed
Beam On Target: 2022
Start of the User Program: 2023
End of Construction for the first 15 instruments: 2025

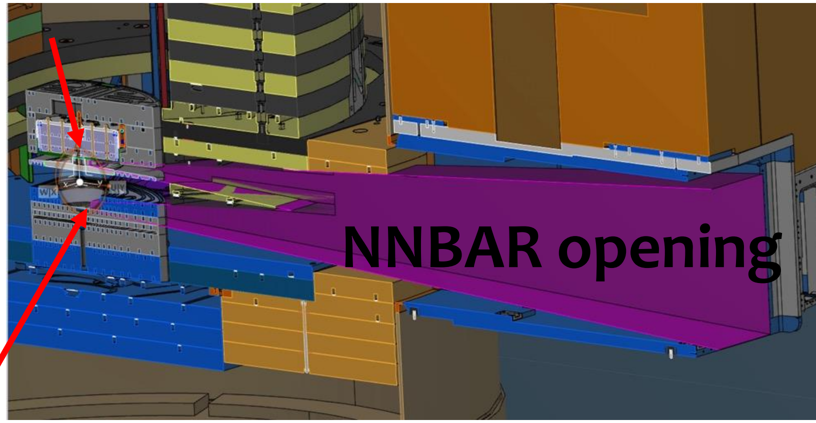
HighNESS project

- Purpose is to develop a Liquid deuterium moderator that can serve a UCN moderator and a VCN moderator





ESS current moderator

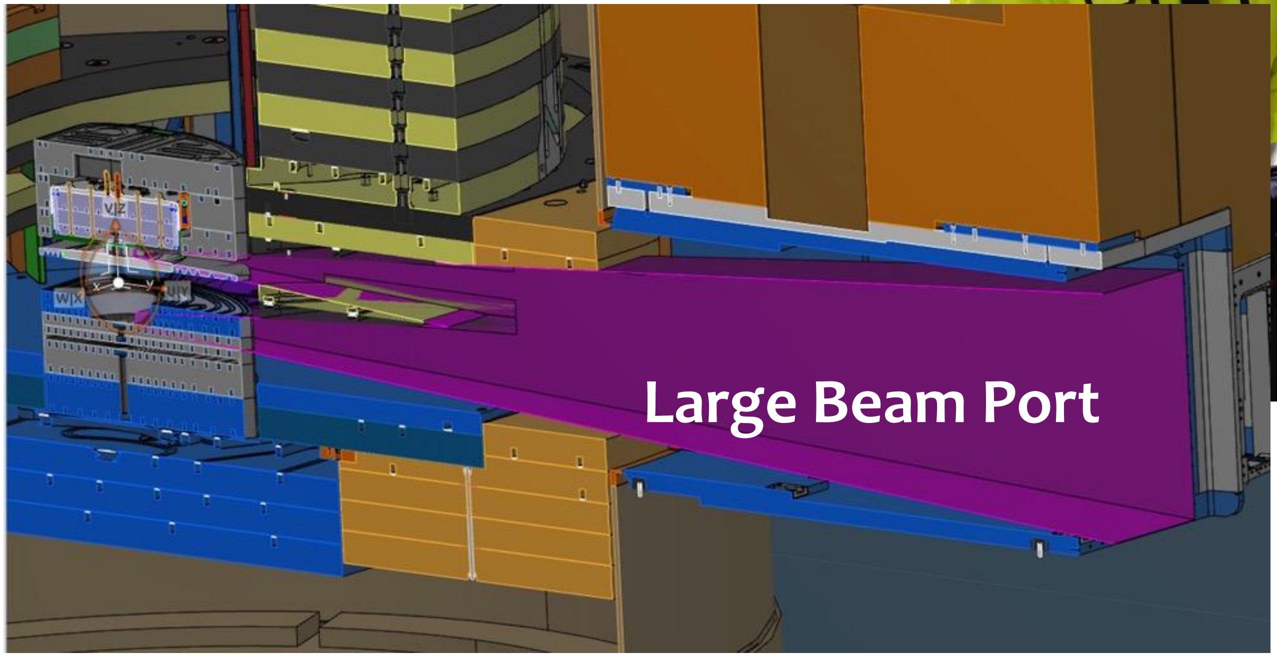


ESS Liquid Deuterium moderator

Large Beam Port

- LBP has been constructed and will provide sufficient intensity for $n \rightarrow \bar{n}$ search
- Room for 200 m of large diameter neutron beamguide

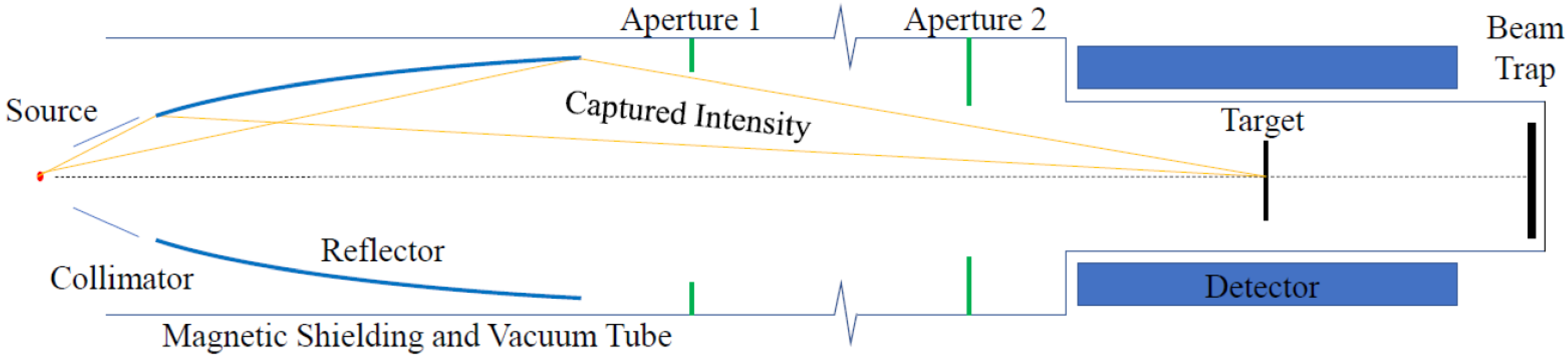
NNBar collaborators at the ESS linac



"The Large Beam Port is an opportunity to broaden the ESS mission"

Rikard Linander, Head of the ESS Target Division

Overview: NNbar experiment



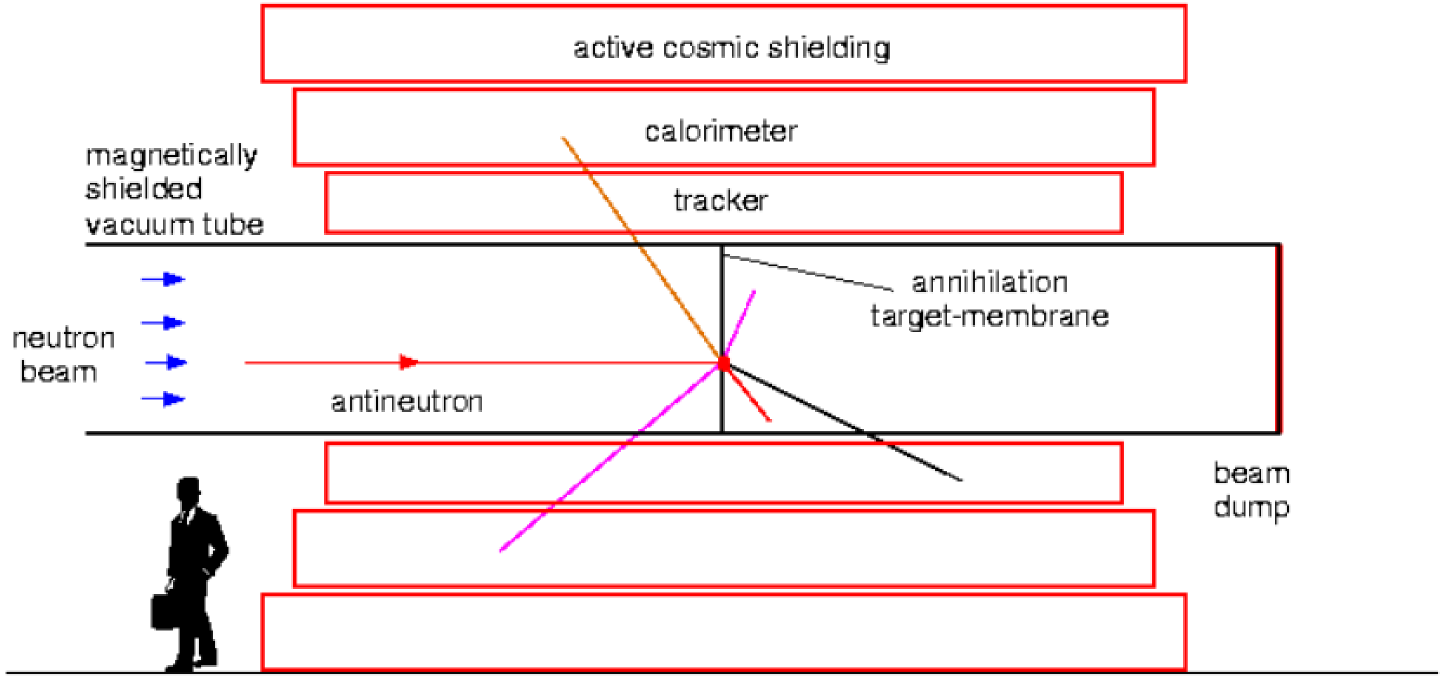
- High-m elliptical/ballistic “super-mirror” reflector
  - free flight time in FOM is time since last bounce – minimize bounces
- Residual B field < 5 nT

- Residual vacuum < 10^{-5} Pa
- NNBar detector can be background-free (as in ILL experiment)
- The goal will be to reach ×**1000** sensitivity of ILL experiment

M. Frost, UTK Ph.D. dissertation
NNBar at ESS whitepaper, arXiv:2006.04907

NNBar detector

- Thin carbon foil target
  - Large $\bar{n}$ annihilation x-s, mostly transparent to n's
- Total energy of event very large for CN beam
- Background suppression:
  - precise vertex ID
  - good resolution
  - beam structure
- Background measurement:
  - magnetic field on/off or multiple targets



$$\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})$$

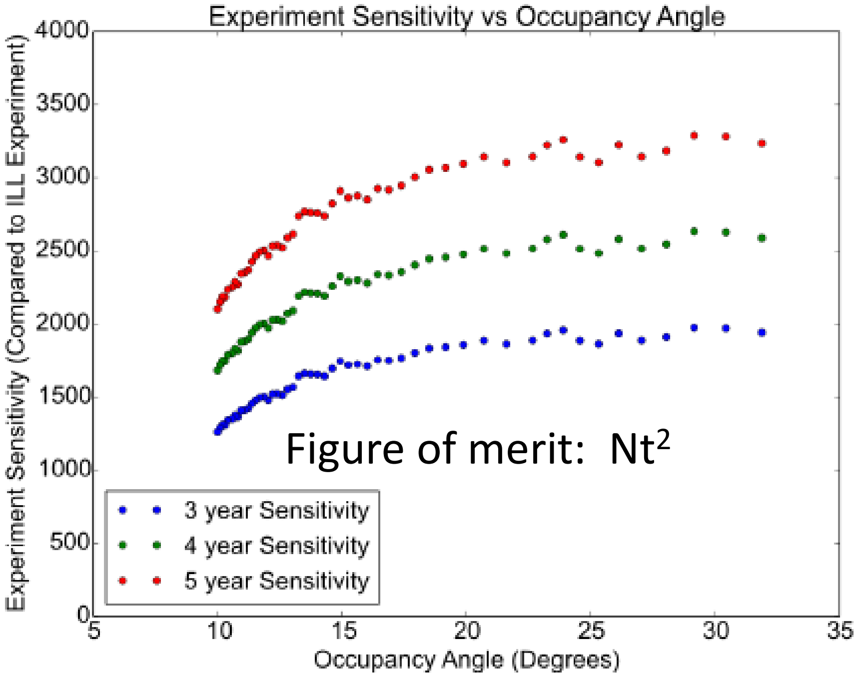
Annihilation target: ~100μ thick Carbon film

$\sigma_{annihilation} \sim 4$ Kb $\quad \sigma_{nC\ capture} \sim 4$ mb

vertex precisely defined. No background was observed at ILL

Factors improvement over ILL experiment

Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

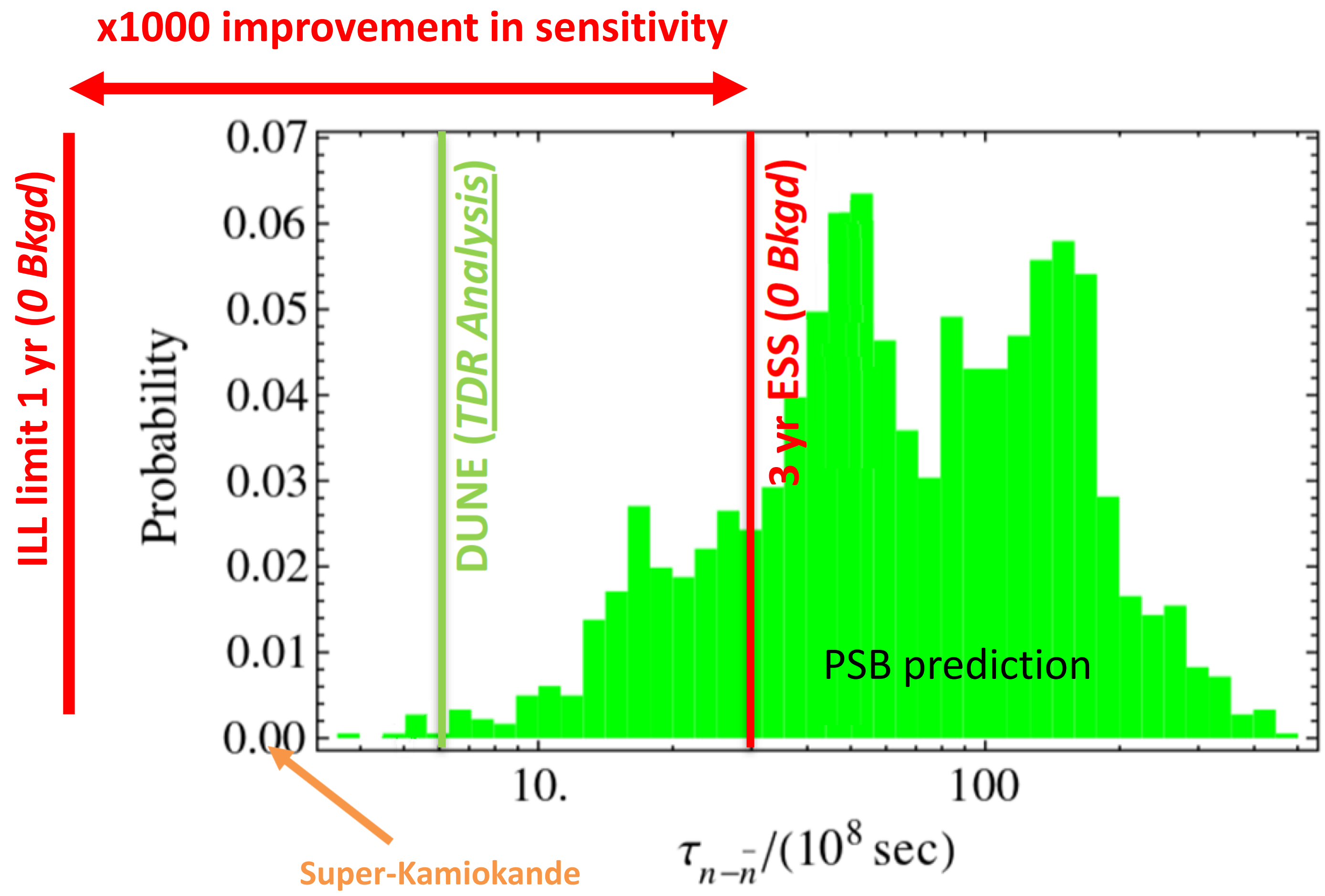


- 50% detection efficiency (as in ILL), 200 m baseline
- Gains in intensity from optimized design including Large Beam Port
- Large gains from neutron reflector: supermirror reflectors now commercially available (m=6) --> active R&D ongoing, J-PARC collaborators achieving m>>10
- $\times$ 1000 increase in sensitivity, reaching $\tau \sim$ 2-3×10^9s
    - Full quantification of sensitivity a component of HighNESS program

NNBar at ESS whitepaper, arXiv:2006.04907

Comparison of Sensitivity

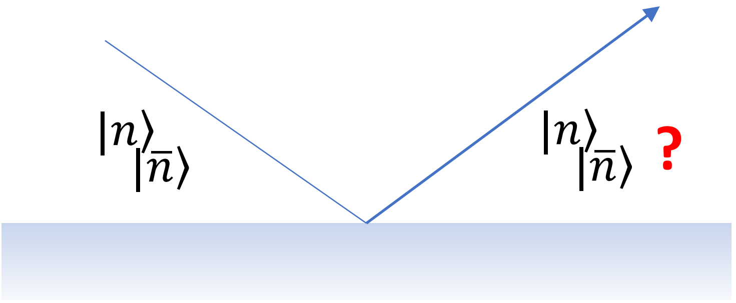
- Next generation experiments start to probe e.g. Post Sphaleron Baryogenesis
  - Green: range of possible oscillation times predicted by PSB model [1]
- Recent preliminary Super-K result approaching that of lower DUNE limit
  - Aggressive background mitigation techniques underway
- Free neutron search complementary and competitive—zero backgrounds



[1] PRD 87 115019 (2013)
DUNE Far Detector Technical Design Report Volume II: DUNE Physics, arXiv:2020.03005
Adapted from J. Barrow, BLV 2019

Clock reset and implications

- Baseline assumes free flight time since last bounce
  - Bounce stops oscillation clock... or does it?
- Antineutrons can bounce!
  - With appropriate choice of material potential, n and $\bar{n}$ wavepackets can continue to propagate coherently
- Implications very exciting—allowing few bounces reduces required diameter, complexity and cost of experiment
  - Can we understand quantum decoherence from spin-dependent polarized neutron absorption?
  - Needs better understanding of antineutron scattering lengths: investigate with antiprotons?
- Important to study: **but not currently the baseline**



Can we use

$$\begin{bmatrix} \uparrow \\ \downarrow \end{bmatrix} \rightarrow \begin{bmatrix} \uparrow \\ \rho e^{i\varphi} \downarrow \end{bmatrix}$$

To learn about

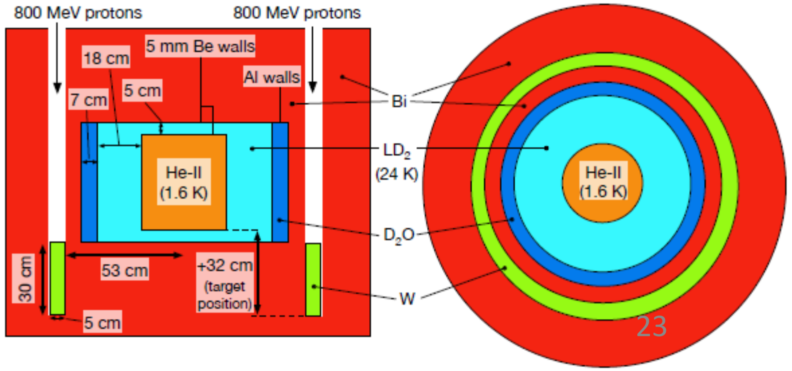
$$\begin{bmatrix} n \\ \bar{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi} \bar{n} \end{bmatrix}$$

W. M. Snow

Kerbikov, PLB 795 (2019) 362-365
Nesvizhevky, Gudkov, Protasov, Snow, Voronin, PRL 122 (2019) 221802

Other sources to consider

- Green field opportunity at ESS in next decade
  - Large Beam Port now constructed
- Large volume UCN-based $n \rightarrow \bar{n}$ search at ESS (based on PNPI design)
- ILL with improved optics/baseline
- ORNL HFIR
  - assume 200 m baseline, possible if future cold guide upgrade; could have similar sensitivity to ESS
- Ideas for future exploration
  - “Inverse geometry” spallation UCN source
  - Vertical neutron “fountain” or drop
  - Very Cold Neutron sources



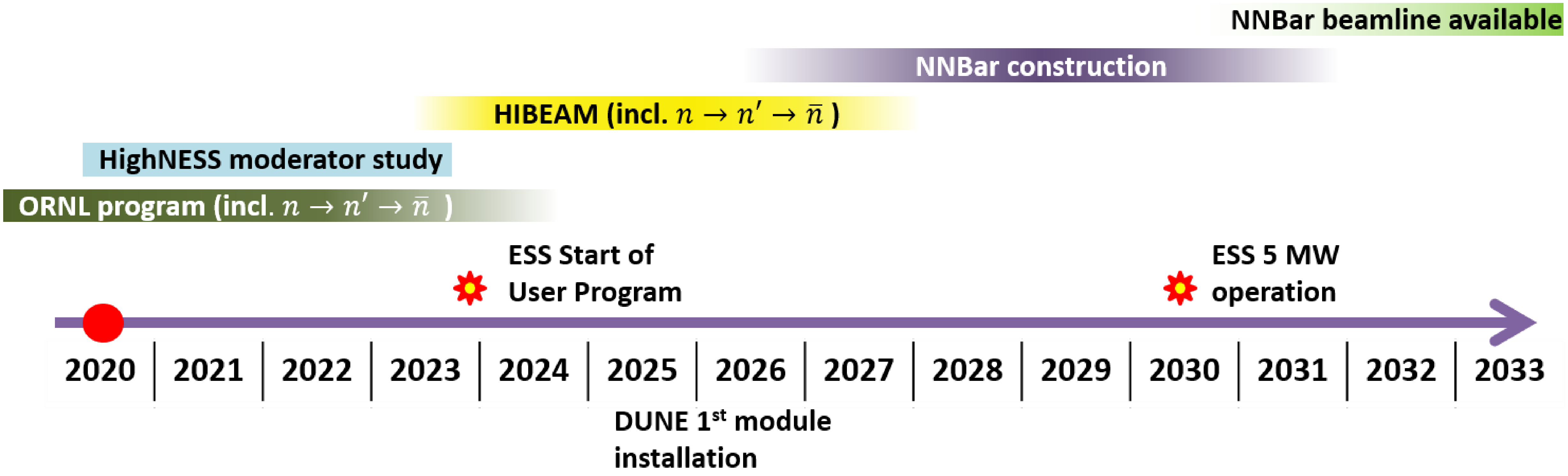
Leung et al, *J.Appl.Phys.* 126 (2019) 22, 224901

R&D Path to NNBar at ESS

- NNBar is a large, costly project
  - Large supermirror guides and magnetic shield largest fraction of cost
- Staged program of development, with complementary science along way
  - Earliest stages at ORNL (now!): searches for $n \rightarrow n'$, $n \rightarrow n' \rightarrow \bar{n}$ oscillations
  - HIBEAM@ANNI ~ 2025: improve above searches + similar sensitivity to $n \rightarrow \bar{n}$ as ILL
  - NNbar > 2030: x1000 improvement for $n \rightarrow \bar{n}$ over ILL
- European collaborators: SRC, HighNESS funding to investigate implementation
  - Detector development and design optimization
  - Simulations of backgrounds and shielding
  - Moderator design and engineering work
  - Address uncertainties in cost of experiment
- Collaboration also investigating tests of new concepts e.g. clock reset

NNBar at ESS whitepaper, arXiv:2006.04907

Timeline for future $n \to \bar{n}$ searches

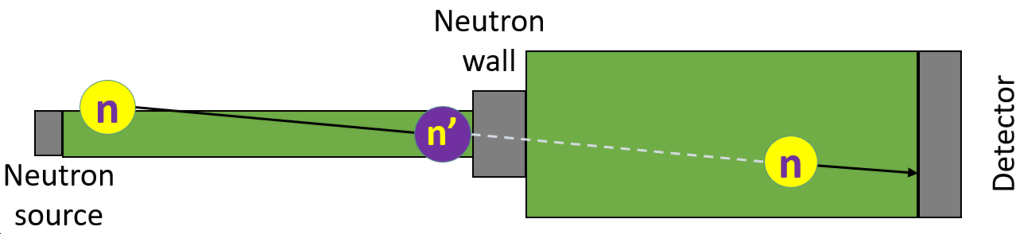


- Includes ongoing R&D in advanced neutron optics, $\bar{n}$ detector prototyping, investigating clock reset concepts...

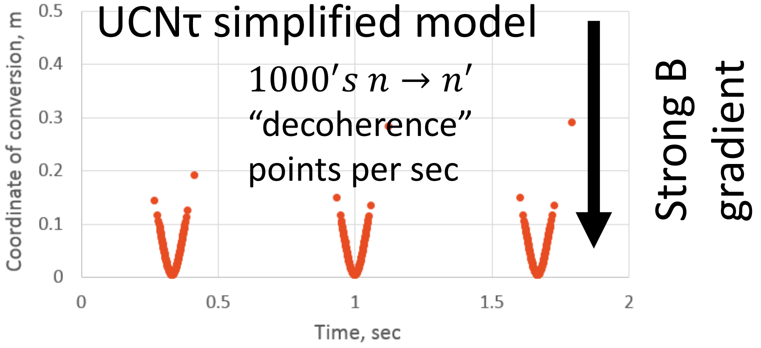
nn' Mixing: Complementary Science

Small mass splitting due to B' will suppress oscillation, search for *resonance* in B scan

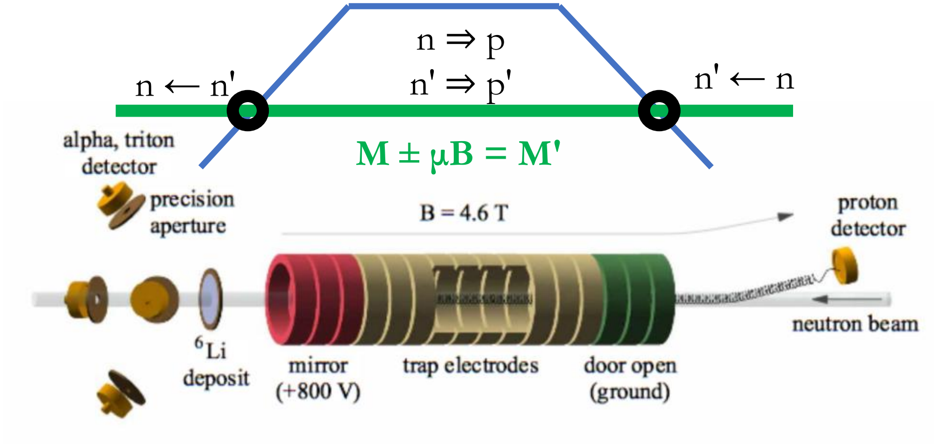
Shining neutrons through a wall



Transition Magnetic Moment (TMM) suggested to explain ultracold neutron lifetime



Small mass splitting (large B field) suggested to explain cold neutron lifetime



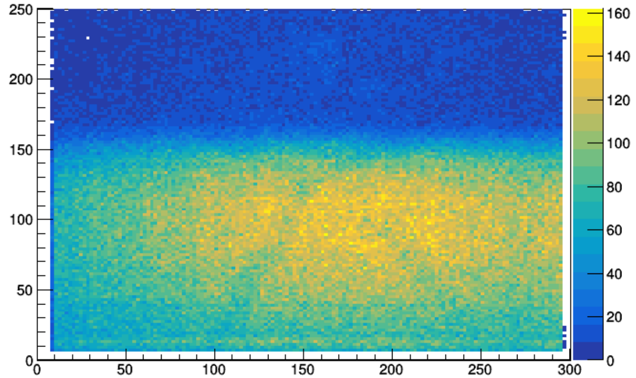
Extend nn' mixing to include $\bar{n}\bar{n}'$

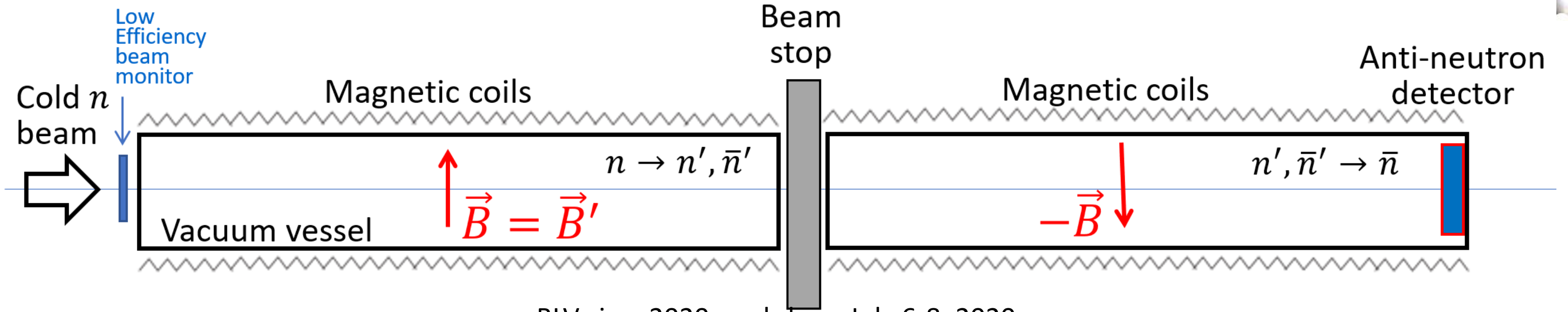
$$\mathscr{H} = \begin{pmatrix} m_n + \vec{\mu}_n \vec{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \alpha_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m_n - \vec{\mu}_n \vec{B} & \alpha_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \alpha_{n\bar{n}'} & m_{n'} + \vec{\mu}_{n'} \vec{B}' & \varepsilon_{n\bar{n}} \\ \alpha_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m_{n'} - \vec{\mu}_{n'} \vec{B}' \end{pmatrix}$$

Overview of previous UCN-based $n - n'$ searches: Berezhiani et al, EPJC 78 (2018) 717
Recent and planned UCN-based searches: Abe et al, EPJ Web Conf 219 (2019) 07001

Program of $n \rightarrow n'$ Searches at ORNL

- Utilizing existing neutron scattering instruments in collaboration with instrument scientists
  - HFIR GP-SANS: 15 m + 20 m beam guides
- First experimental search for small mass splitting completed at ORNL SNS
  - Results in analysis, details to be presented at **August BNV=2 Workshop**
  - Sensitivity to refute or confirm $n \rightarrow n'$ as explanation for lifetime anomaly
- Staged program to lead up to $n \rightarrow n' \rightarrow \bar{n}$ search





EPJ Web Conf 219, 07002 (2019)

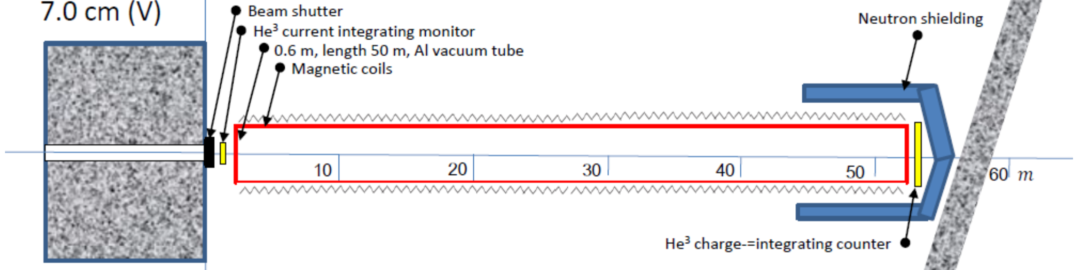
HIBEAM: ~2023 – 2027

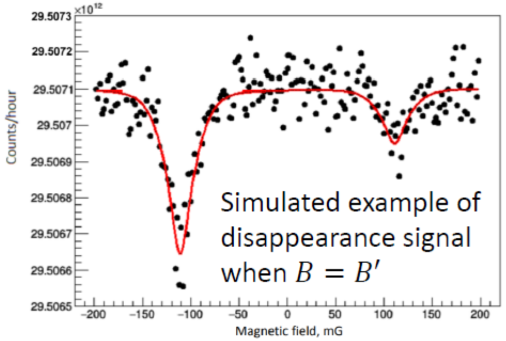
- greatly improve sensitivity over ORNL with optimized beamline

22m

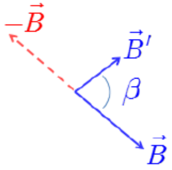
HIBEAM Experiment Layout at ESS for n disappearance measurement (2023-2027)

beam hole:
11.2 cm (H)
7.0 cm (V)





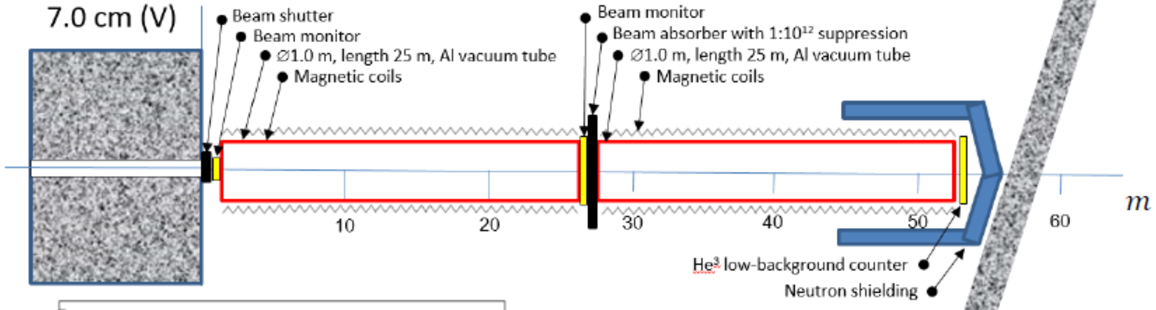
intensity through dia 1 m @ 54 m is 6.4E+10 n/s
ESS @ 1 MW

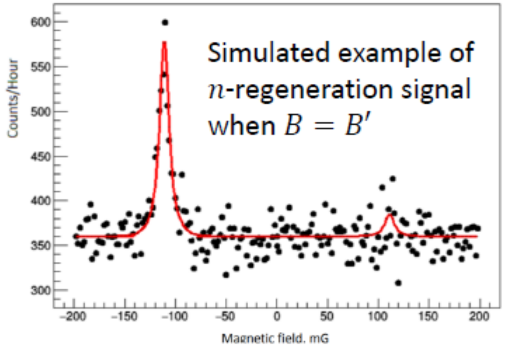


HIBEAM Experiment Layout at ESS for n-regeneration measurement 2023-2027

beam hole:
11.2 cm (H)
7.0 cm (V)

$n \to n'$ $n' \to n$





intensity through ∅1 m at z=54 m is 6.4E+10 n/s
ESS @ 1 MW

Detection of resonance via variation of magnetic field B will also demonstrate the existence of mirror photons field γ'

Summary

- Searches for Baryon Number Violation strongly motivated
  - Neutron oscillations access underexplored space in worldwide program
  - Resolution of questions on baryon asymmetry of universe, alternate models of dark matter
- Strong limits from complementary approaches: free and bound neutron searches
  - Activity ongoing with preliminary results from SK and R&D towards NNBar
- Future large detectors like DUNE represent great opportunity
  - Goal to aggressively push down backgrounds, promising analysis developments on horizon
- Mature concept for large scale free search in NNBar at ESS
  - Large Beam Port now constructed; investigation of experiment implementation underway
  - Staged program beginning at ORNL can pave the path to a successful BNV program
- Strong interdisciplinary community in nuclear physics and neutronics—timely opportunities for US HEP leadership!

LJB is supported by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy, and by the U.S. Department of Energy, Office of Nuclear Physics under contract number DE-AC05-00OR2272